Energy 57 (2013) 766–774

Contents lists available at SciVerse ScienceDirect

Energy

journal homepage: www.elsevier.com/locate/energy

# Exergetic sustainability analysis of LM6000 gas turbine power plant with steam cycle

Hakan Aydin

*Aeronautical Engineer, TUSAS Engine Industry (TEI), Eskisehir, Turkey*

ARTICLE INFO

*Article history:*
Received 10 January 2013
Received in revised form
10 March 2013
Accepted 19 May 2013
Available online 25 June 2013

*Keywords:*
Gas turbine engine
Power plant
Exergy
Sustainability indicator
Energy

ABSTRACT

The aim of this study is to develop the exergetic sustainability indicators in order to determine sustainability aspects of gas turbine engine (GTE) based power plant. For this purpose, first a comprehensive exergy analysis of GTE is carried out then the exergetic sustainability indicators are calculated for two power plant configuration, case A for LM6000 GTE based power plant, case B for LM6000 GTE based power plant with steam turbine cycle. The investigated exergetic sustainability indicators are exergy efficiency, waste exergy ratio, exergy destruction factor, recoverable exergy ratio, environmental effect factor and exergetic sustainability. At maximum power operation, case A power plant generates 43.3 MW electricity power whereas 54.3 MW of electricity power is generated by case B power plant thanks to steam turbine cycle contribution. Results show that exergetic sustainability index is obtained as 0.651 for case A and 0.978 for case B power plant. Steam turbine cycle results in improvement of overall efficiency and reviewed exergetic sustainability indicators evidently. Decrease of waste exergy ratio leads to decrease of environmental effect factor and increase both exergetic efficiency and exergetic sustainability index. Moreover, studying these parameters indicates how much improvement is possible for GTE to achieve better sustainability.



## 1. Introduction

Sustainability is becoming the more and more important with environmental and cost reduction aspects. With the increase of world's energy need, the number of gas turbine engine based power plants generating electricity and heat increase the year to year. Increasing energy source costs and negative impacts of wastes on environment lead to great importance of sustainable/renewable energy sources using and improve the efficiency to minimize environmental intrusions. Exergy analysis is an essential tool to expose the impacts of a power generating device on exergy-based sustainability. Sustainability is necessary to overcome current ecological, economic, and developmental problems [1]. Energy sustainability is becoming a global necessity, given the pervasive use of energy resources globally, the impacts on the environment of energy processes and their reach beyond local to regional and global domains, and the increasing globalization of the world's economy [2]. From an environmental perspective, using energy with high efficiency reduces pollutant emissions and harm to ecological systems. For a given output, less fuel is needed when efficiency increases and less waste is released. These benefits lead to increased lifetimes for energy resources and greater sustainability [3].

Cogeneration, or combined heat and power (CHP), is the simultaneous production of electricity and usable heat. In conventional power plants, a large amount of heat is produced but not used. By designing systems that can use the heat, the efficiency of energy production can be increased from current levels that range from 35% to 55%, to over 80%. There are conceptually three different cogeneration plants: the steam turbine based, gas turbine based, and diesel engine based plant. The main subsystems of power plant are: gas turbine engine (GTE), gas turbine and steam turbine generators, heat recovery steam generator (HRSG), steam turbine, condenser and pumping units.

Exergy analysis is an effective tool which provides insights into the performance of energy conversion systems, and highlights the possible improvements [4]. Exergy analyses have recently been employed for analysis, design, performance improvement and optimization of thermal systems, including CHP (combined heat and power) plants. It is well-known that exergy can be used as a potential tool to determine location, type and true magnitude of exergy losses (or destructions) [5]. Therefore, it can play an important issue in developing strategies and in providing

*E-mail address:* tei.hakan@gmail.com.

0360-5442/$ – see front matter 
http://dx.doi.org/10.1016/j.energy.2013.05.018

guidelines for more effective use of energy in the existing power plants [6]. Exergy methods can also play a role in improving environmental and economic performance [7]. It is observed that exergy is a powerful tool for understanding and improving the sustainability of processes and systems.

In terms of exergy based sustainability parameters, Midilli and Dincer [8] developed some new exergetic parameters for a PEM fuel cell and they've conducted comprehensive parametric study on how system and operation related aspects affect efficiency, environmental impact and sustainable development. Aydin [9] studied exergetic sustainability indicators for commercial airplane and turbofan engine. In another study, the environmental and sustainability aspects of the recirculating aquaculture system have parametrically been studied based on some actual data [10]. Moreover, green energy strategies for sustainable development have been investigated and some key parameters have been introduced [11]. The authors noted that the green energy supply and progress should be encouraged by governments and other authorities for a green energy replacement of fossil fuels for more environmentally benign and sustainable future. In another article, the study on hydrogen as a renewable and sustainable solution for reducing global fossil fuel consumption and combating global warming has been reviewed and environmental impact results are compared with the ones obtained for fossil fuels [12].

A comprehensive exergy, exergoeconomic and environmental impact analysis and optimization is reported for several combined cycle power plants by Ahmadi, Dincer and Rosen [13]. The optimization results demonstrates that $CO_2$ emissions are reduced by selecting the best components and using a low fuel injection rate into the combustion chamber. In the literature, some additional studies on energy, exergy, exergoeconomic and environmental analyses cogeneration, trigeneration power plants, aircraft turbofan, turboprop and turboshaft engines are executed [3–5,14–28].

In this article, first a comprehensive exergy analysis of LM6000 GTE based power plant is performed and then exergy parameters such as exergy efficiency, exergy losses/destructions, relative exergy, destruction ratio, fuel depletion ratio, productivity lack ratio, and potential improvement rates are calculated based on actual data.

In addition to exergy analysis of the system the exergetic sustainability indicators of the LM6000 GTE for two power plant configurations are calculated and evaluated. The reviewed two configurations are Case A for LM6000 base power plant and in Case B for the LM6000 power plant with implemented steam turbine cycle. In open literature, there's no study performed on exergetic sustainability indicator analysis of GTE based power plant that makes this paper original.

The investigated exergy-based sustainability indicators are as below,

- Exergy efficiency
- Waste exergy ratio
- Recoverable exergy ratio
- Exergy destruction factor
- Environmental effect factor
- Exergetic sustainability index

## 2. LM6000 system description

The General Electric LM6000 gas turbine is a stationary gas turbine that is derived from the CF6 jet engines family. The GE LM6000 PC is rated to provide more than 43 MW at ISO conditions. More than 1000 LM6000 gas turbine engine have been produced that they had over 21 million hours of operation. They're used in marine application and power plants to produce electricity and heat. The aircraft version of the engine is called the CF6-80C2 turbofan engine and is used to drive several types of "wide body" commercial aircraft, including the Boeing 747-400 [29,30]. The illustrated diagram, station numbering and main component of LM6000 is shown in Fig. 1 for case A and in Fig. 2 for case B.

The LM6000 gas turbine is a dual-rotor, concentric drive-shaft, gas turbine capable of driving a load from the front and/or rear of the low-pressure (LP) rotor. It has a 5-stage low-pressure compressor (LPC), a 14-stage variable-geometry high-pressure compressor (HPC), an annular combustor, a 2-stage high-pressure turbine (HPT), a 5-stage low-pressure turbine (LPT), an accessory gearbox (AGB) assembly, and accessories (LM6000 GEK 105059,2003).

The air is compressed in LPC and HPC compressors by the ratios of approximately 2.4 and 12, resulting in a total compression ratio of 30 relative to ambient. From the HPC, the air is directed into the signal annular combustor section, where it mixes with the fuel from fuel nozzles. The hot gas that results from combustion is directed into the HPT that drives the HPC. This gas further expands through the LPT, which drives the LPC and the output load.

*Assumptions*

In this study, the assumptions made are listed below

i. The air and combustion gas flows in the engine are assumed to behave ideally.
ii. The combustion reaction is complete
iii. Compressors and turbines are assumed to be adiabatic

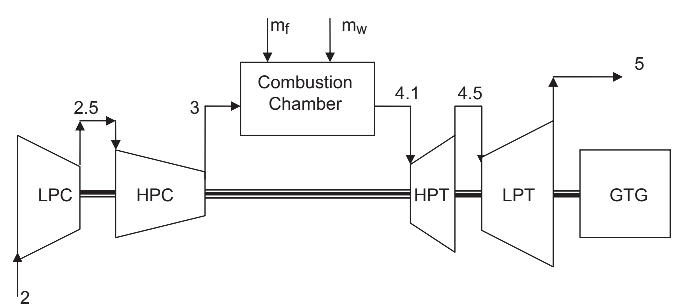


**Fig. 1.** Schematic illustration of the LM6000 GTE based power plant (case A).

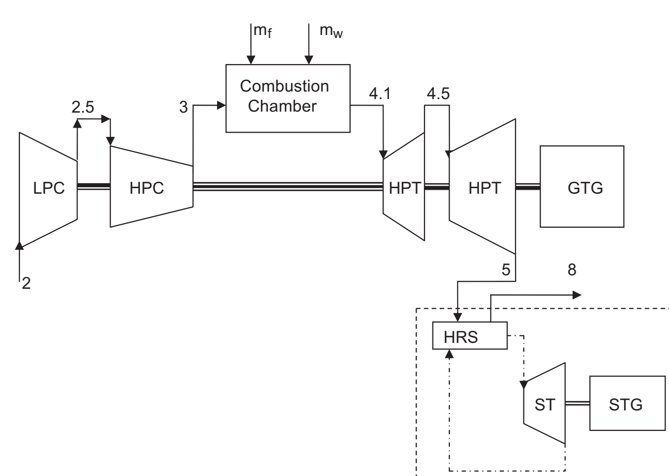


**Fig. 2.** Schematic illustration of the LM6000 GTE based power plant with steam turbine cycle (Case B).

iv. Ambient temperature and pressure values are 288 K and 100.7 kPa, respectively.
v. The exergy analyses are performed for the lower heating value (LHV) of natural gas which is accepted as 44,600 kJ/kg.
vi. The kinetic and potential exergies are neglected
vii. Chemical exergy is neglected other than combustor
viii. Steam cycle power generation is accepted as 11 MW which's about ¼ of LM6000 gas turbine engine power.

*Airflow*

119.5 kg/s of airflow is taken into compressor at ambient temperature of 288 K and ambient pressure of 100.7 kPa. About 18% of air is burned with 2.39 kg/s natural gas in combustion process. In modern gas turbine engines, some of the compressor air is used for ancillary purposes, such as cooling, sealing and thrust balancing. In this study the cooling airflow is neglected since it doesn't make significant effect in results.

*Fuel consumption and power*

The engine can be operated with either gas or liquid fuel. In the LM6000 GTE based power plant natural gas is consumed. Its composition is given by (1) [6–17].

$$0.9334CH_4 + 0.00211C_2H_6 + 0.00029C_3H_8 + 0.00012C_4H_{10} + 0.06408N_2 \tag{1}$$

*Combustion and emissions*

For 119.5 kg air, 2.39 kg natural gas and 2.3 kg water, the combustion reaction, for both case A and case B, expressed in terms of mole fractions of the gas components is as follows,

$$\begin{pmatrix} 0.9334CH_4 \\ +0.00211C_2H_6 \\ +0.00029C_3H_8 \\ +0.00012C_4H_{10} \\ +0.06408N_2 \end{pmatrix} + 29.01 \begin{pmatrix} 0.7748N_2 \\ +0.2059O_2 \\ +0.0003CO_2 \\ +0.019H_2O \end{pmatrix} + 0.9H_2O \Rightarrow \begin{pmatrix} 0.9856CO_2 \\ +2.392H_2O \\ +4.523O_2 \\ +22.533N_2 \end{pmatrix} \tag{2}$$

The injection of water or steam into the flame area of a turbine combustor provides a heat sink, which lowers the flame temperature and thereby reduces thermal $NO_x$ formation. In order to increase the service life, the parts such as turbine blades, nozzle vanes etc. exposed to hot gases are generally coated with special processes and cooled by bleed air from compressor. After the combustion reaction, the mass of combustion gases are obtained as 6.23 kg/s for $CO_2$, 6.18 kg/s for $H_2O$, 20.82 kg/s for $O_2$ and 90.7 kg/s for $N_2$.

*Specific heat capacities of air and combustion gas*

The specific heat capacity of the combustion gases is obtained by the composition of equations of each component in its mass percentage by (3) [31].

$$c_{P,\text{gas}}(T) = 1.00397 + \frac{2.429 \times T}{10^5} + \frac{1.63 \times T^2}{10^7} - \frac{6.966 \times T^3}{10^{11}} \tag{3}$$

where the unit of temperature is K. Hot gases $R$ value has been calculated as 0.293 kJ kg$^{-1}$. For cold air [32],

$$c_{P,\text{hava}}(T) = 1.04841 - 0.000383719 \times T + \frac{9.45378 \times T^2}{10^7} - \frac{5.49031 \times T^3}{10^{10}} + \frac{7.92981 \times T^4}{10^{14}} \tag{4}$$

## 3. Exergy analyses

In order to obtain the exergy-based sustainability indicators of GTE based power plant, the primary step should be to perform the exergy analysis by employing the second-law of thermodynamics. Data used in this analysis are listed in Table 1 for different points in the engine. This data is taken from LM6000 quick reference guide [33]. A few of unmeasured temperature and pressure values are derived from parametric cycle analysis. Having all required flow parameters the exergy flow in inlet and exit of main components are calculated through Eqs. (5)–(32).

The total exergy of a system can be calculated by Eq. (5) as the sum of kinetic, potential, physical and chemical exergies [34];

$$\dot{E}x = \dot{E}x_{kn} + \dot{E}x_{pt} + \dot{E}x_{ph} + \dot{E}x_{ch} \tag{5}$$

where the terms $\dot{E}x_{kn}$, $\dot{E}x_{pt}\dot{E}x_{ph}$ and $\dot{E}x_{ch}$ denote the kinetic, potential, physical and chemical exergies, respectively. For a unit mass,

$$\dot{E}x_{kn} = \dot{m}\frac{V^2}{2} \tag{6}$$

$$\dot{E}x_{pt} = \dot{m}gz \tag{7}$$

The specific physical exergy for air and combustion gaseous with constant specific heat is obtained from Ref. [35]

$$\dot{E}x_{ph} = \dot{m}[(h - h_0) - T_0(s - s_0)] \tag{8}$$

where $h$ is enthalpy, $s$ is entropy and the subscript zero indicates properties at the restricted dead state of $P_0$ and $T_0$ [34].

$$\dot{E}x_{ph} = \dot{m}c_{P(T)}\left[(T - T_0) - T_0\ln\left(\frac{T}{T_0}\right) + RT_0\ln\left(\frac{P}{P_0}\right)\right] \tag{9}$$

The specific chemical exergies of natural gas on a unit mass basis can be determined from Eq. (10) [17,36].

**Table 1**
LM6000 GTE power plant thermodynamic data.

| Station no | Location | Mass flow (kg s$^{-1}$) | Temperature (K) | Pressure (kPa) | Exergy flow (kW) |
|---|---|---|---|---|---|
| 0 | Air | 119.5 | 288 | 100.7 | 0 |
| 2 | LPC inlet | 119.5 | 288 | 100.7 | 0 |
| 2.5 | LPC outlet | 119.5 | 383 | 247 | 10.33 |
| 2.5 | HPC inlet | 119.5 | 383 | 247 | 10.33 |
| 3 | HPC outlet | 119.5 | 815 | 3034 | 63.03 |
| 3 | Combustor inlet | 119.5 | 815 | 3034 | 63.03 |
| 4 | Fuel | 2.39 | 293 | 2200 | 111.1 |
| 4 | Water | 2.3 | 293 | 1700 | 0.05 |
| 4.1 | Combustor outlet | 124 | 1550 | 2882 | 148.27 |
| 4.1 | HPT inlet | 124 | 1550 | 2882 | 148.27 |
| 4.8 | HPT outlet | 124 | 1144 | 724 | 85.56 |
| 4.8 | LPT inlet | 124 | 1144 | 724 | 85.56 |
| 5 | LPT outlet | 124 | 770 | 111 | 27.8 |

Source: LM6000 Quick Reference Guide [33].

$$\frac{\varepsilon_{ch,F}}{H_a} = \gamma_F \cong 1.033 + 0.0169\frac{H}{C} - 0.0698\frac{1}{C} \tag{10}$$

where $\gamma_f$ denotes the fuel exergy grade function which is calculated to be 1.0308 for natural gas. The natural gas physical exergy is calculated by Eq. (9). Exergy efficiency ($\eta_{ex}$) is defined as the ratio of total exergy output to total exergy input, i.e.

$$\eta_{ex} = \frac{\dot{E}x_{out}}{\dot{E}x_{in}} \tag{11}$$

Exergy destruction and loss is calculated from the difference between inlet and outlet exergy values.

$$\dot{E}x_{loss,dest} = \dot{E}x_{in} - \dot{E}x_{out} \tag{12}$$

The fuel depletion ratio is found by the ratio of the exergy consumption of $k$ith component to the fuel exergy rate input of engine by Eq. (13).

$$\delta_i = \frac{\dot{E}x_{dest,i}}{\dot{E}x_{fuel}} \tag{13}$$

Irreversibility of a component can be calculated by dividing component destruction exergy to total destructed exergy of system as shown below formula [3],

$$X_i = \frac{\dot{E}x_{dest,i}}{\dot{E}x_{dest,tot}} \tag{14}$$

Another exergy parameters is 'exergetic improvement potential rate' can be calculated as follows [37],

$$I\dot{P} = (1-\eta_{ex})\left(\dot{E}x_{in} - \dot{E}x_{out}\right) \tag{15}$$

Exergy parameters of LM6000 GTE main engine components which are low pressure compressor, high pressure compressor, combustor, low pressure turbine and high pressure turbine can be computed by Eqs. (16)–(32)

*Low Pressure Compressor;*

$$\sum \dot{E}x_{in,LPC} - \sum \dot{E}x_{out,LPC} = \sum \dot{E}x_{dest,LPC} \tag{16}$$

$$\dot{W}_{LPC} + \dot{E}x_2 - \dot{E}x_{25} = \sum \dot{E}x_{dest,LPC} \tag{17}$$

$$\dot{W}_{LPC} = \frac{\dot{m}_{LPC}\left(\overline{h}_{25} - \overline{h}_2\right)}{M_A} \tag{18}$$

$$\eta_{ex,LPC} = \frac{\dot{E}x_{25} - \dot{E}x_2}{\dot{W}_{LPC}} \tag{19}$$

*High Pressure Compressor;*

$$\sum \dot{E}x_{in,HPC} - \sum \dot{E}x_{out,HPC} = \sum \dot{E}x_{dest,HPC} \tag{20}$$

$$\dot{W}_{HPC} + \dot{E}x_{25} - \dot{E}x_3 = \sum \dot{E}x_{dest,HPC} \tag{21}$$

$$\dot{W}_{HPC} = \frac{\dot{m}_{HPC}\left(\overline{h}_3 - \overline{h}_{25}\right)}{M_A} \tag{22}$$

$$\eta_{ex,HPC} = \frac{\dot{E}x_3 - \dot{E}x_{25}}{\dot{W}_{HPC}} \tag{23}$$

*Combustor (CC);*

$$\sum \dot{E}x_{in,CC} - \sum \dot{E}x_{out,CC} = \sum \dot{E}x_{dest,CC} \tag{24}$$

$$\dot{E}x_3 + \dot{E}x_{fuel} + \dot{E}x_{water} - \dot{E}x_4 = \sum \dot{E}x_{dest,CC} \tag{25}$$

$$\eta_{ex,CC} = \frac{\dot{E}x_4}{\dot{E}x_3 + \dot{E}x_{fuel}} \tag{26}$$

*High Pressure Turbine (HPT):*

$$\sum \dot{E}x_{in,HPT} - \sum \dot{E}x_{out,HPT} = \sum \dot{E}x_{dest,HPT} \tag{27}$$

$$\dot{E}x_{41} - \left(\dot{W}_{HPT} + \dot{E}x_{45}\right) = \sum \dot{E}x_{dest,HPT} \tag{28}$$

$$\eta_{ex,HPT} = \frac{\dot{W}_{HPT}}{\dot{E}x_{41} - \dot{E}x_{45}} \tag{29}$$

*Low Pressure Turbine (LPT):*

$$\sum \dot{E}x_{in,LPT} - \sum \dot{E}x_{out,LPT} = \sum \dot{E}x_{dest,LPT} \tag{30}$$

$$\dot{E}x_{45} - \left(\dot{W}_{LPT} + \dot{E}x_5\right) = \sum \dot{E}x_{dest,LPT} \tag{31}$$

$$\eta_{ex,LPT} = \frac{\dot{W}_{LPT}}{\dot{E}x_{45} - \dot{E}x_5} \tag{32}$$

## 4. Exergetic sustainability indicators

Sustainability means a supply of energy resources that is sustainably available at reasonable cost and causes no or minimal negative effects. Exergy analysis can also be used to assess the sustainability level of the energy systems. The exergetic sustainability indicators which will be investigated for LM6000 GTE based power plant, in conjunction with environmental impact and sustainable development, are exergy efficiency, waste exergy ratio, recoverable exergy rate, exergy destruction factor, environmental effect factor and exergetic sustainability index [8,10]. These parameters are expected to quantify how LM6000 become more environmentally benign and sustainable. In this chapter, the exergetic sustainability indicators of LM6000 GTE based power plant for case A and case B are developed.

The general mass, energy and exergy balances of the LM6000 GTE for case A and case B power plant configurations are shown in Figs. 7 and 8. The general exergy balance can be written as.

$$\begin{aligned}(\text{Total exergy input}) = {} & (\text{Total useful exergy output}) \\ & + (\text{Total lost exergy output}) \\ & + (\textit{Total destructed exergy})\end{aligned}$$

$$\sum \dot{E}x_{t,in} = \sum \dot{E}x_{u,out} + \sum \dot{E}x_{loss,out} + \sum \dot{E}x_{dest,out} \tag{33}$$

where the total inlet exergy ($\dot{E}x_{t,in}$) can be obtained by sum of chemical exergies of natural gas, air and water entering into the LM6000 as shown in Fig. 8. $\dot{E}x_{u,out}$ is useful exergy which is the electricity power produced by gas generator and steam turbine. Eq. (33) can be arranged as below,

$$\begin{aligned}\sum \dot{E}x_{ch}^{ng} + \dot{E}x_{ch}^{air} + \dot{E}x_{ch}^{water} = {} & \sum \dot{E}x_{u,out} + \sum \dot{E}x_{loss,out} \\ & + \sum \dot{E}x_{dest,out}\end{aligned} \tag{34}$$

Under this solid theoretical background, the exergy-based environmental and sustainability parameters previously

presented in the literature [8,10] are considered and rearranged for the LM6000 GTE power plant as

i. Exergetic efficiency
ii. Waste exergy ratio
iii. Exergy recoverability ratio
iv. Exergy destruction ratio
v. Environmental impact factor
vi. Exergetic sustainability index

*Exergy efficiency* ($\eta_{ex}$)
Exergy efficiency of a power plant can be calculated by ratio of the total useful exergy output which is generated electrical power to the total exergy input [8,35]. For case B, the useful exergy is the sum of electricity power produced by gas generator and steam generators. From this expression the exergetic efficiencies for case A and case B power plants can be written as below,

$$\eta_{ex}^{\text{case A}} = \frac{\dot{E}x_{u,\text{out}}^{\text{case A}}}{\dot{E}x_{t,\text{in}}^{\text{LM6000}}} = \frac{\dot{E}x_{\text{power}}^{\text{GTG}}}{\dot{E}x_{ch}^{ng} + \dot{E}x_{ch}^{\text{air}} + \dot{E}x_{ch}^{\text{water}}} \tag{35}$$

$$\eta_{ex}^{\text{case B}} = \frac{\dot{E}x_{u,\text{out}}^{\text{case B}}}{\dot{E}x_{t,\text{in}}^{\text{LM6000}}} = \frac{\dot{E}x_{\text{power}}^{\text{GTG}} + \dot{E}x_{\text{power}}^{\text{STG}}}{\dot{E}x_{ch}^{ng} + \dot{E}x_{ch}^{\text{air}} + \dot{E}x_{ch}^{\text{water}}} \tag{36}$$

Waste exergy ratio ($r_{we}$)
The aim of power plant is to generate the electricity power. During power plant running some of exergy is destructed in the engine components and also some of exergy is lost by means of hot exhaust gases discharge into environment. So the total waste exergy can be calculated by sum of both destructed exergy and loss exergy of the system. $\dot{E}x_{w,\text{out}}$, waste exergy can be calculated by Eq. (37),

$$\sum \dot{E}x_{\text{we,out}} = \sum \dot{E}x_{\text{dest,out}} + \dot{E}x_{\text{loss,out}} \tag{37}$$

Waste exergy ratio can be calculated by ratio of total waste exergy to the total inlet exergy [8,10].

$$\text{Waste exergy ratio} = (\text{Total waste exergy out})/(\text{Total exergy inlet}) \tag{38}$$

As written in algebraic form waste exergy ratios for case A and case B power plants are outlined by Eqs. (39) and (40);

$$r_{we}^{\text{case A}} = \frac{\sum \dot{E}x_{\text{we},o}^{\text{case A}}}{\sum \dot{E}x_{t,\text{in}}^{\text{LM6000}}} = \frac{\dot{E}x_{\text{dest,out}}^{\text{LM6000}} + \dot{E}x_{\text{loss,out}}^{\text{case A}}}{\dot{E}x_{ch}^{ng} + \dot{E}x_{ch}^{\text{air}} + \dot{E}x_{ch}^{\text{water}}} \tag{39}$$

$$r_{we}^{\text{case B}} = \frac{\sum \dot{E}x_{\text{we},o}^{\text{case B}}}{\sum \dot{E}x_{t,\text{in}}^{\text{LM6000}}} = \frac{\dot{E}x_{\text{dest,out}}^{\text{LM6000}} + \dot{E}x_{\text{loss,out}}^{\text{case B}}}{\dot{E}x_{ch}^{ng} + \dot{E}x_{ch}^{\text{air}} + \dot{E}x_{ch}^{\text{water}}} \tag{40}$$

*Recoverable exergy rate* ($r_{re}$)
Exergy recoverability ratio indicates the exergy potential that is possible to be recovered in the system [8,10]. The destructed exergy values of LM6000 GTE main components cannot be recoverable since they depend on the design and operational characteristics and can only be reduced by improving the component efficiencies by design changes. However, some part of loss exergy which's due to hot exhaust gases discharged to environment for both case A and case B power plant configurations can be recoverable. The loss exergy can be used as heating purposes but recovery process of the heat requires additional investments and systems. It'll be assumed that 90% of loss exergy can be converted to heat energy with the implemented system.

$$\text{Recoverable exergy ratio} = \text{Recoverable exergy/Total exergy inlet} \tag{41}$$

For case A,

$$r_{re}^{\text{case A}} = \frac{\sum \dot{E}x_{re,o}^{\text{case A}}}{\sum \dot{E}x_{t,\text{in}}^{\text{LM6000}}} = \frac{0.9x\dot{E}x_{\text{loss,out}}^{\text{case A}}}{\dot{E}x_{ch}^{ng} + \dot{E}x_{ch}^{\text{air}} + \dot{E}x_{ch}^{\text{water}}} \tag{42}$$

For case B,

$$r_{re}^{\text{case B}} = \frac{\sum \dot{E}x_{re,o}^{\text{case B}}}{\sum \dot{E}x_{t,\text{in}}^{\text{LM6000}}} = \frac{0.9x\dot{E}x_{\text{loss,out}}^{\text{case B}}}{\dot{E}x_{ch}^{ng} + \dot{E}x_{ch}^{\text{air}} + \dot{E}x_{ch}^{\text{water}}} \tag{43}$$

*Exergy destruction factor* ($f_{\text{exd}}$)
Exergy destruction factor is significant parameter indicating the decrease of the positive effect of the engine on exergy-based sustainability. Exergy destruction factor can be calculated by the ratio of exergy destruction to the total exergy input [8,10].

$$\text{Exergy destruction factor} = \text{Exergy destruction/Total exergy input} \tag{44}$$

For case A and case B it can be written as in algebraic form,

$$f_{\text{exd}}^{\text{case A}} = f_{\text{exd}}^{\text{case B}} = \frac{\dot{E}x_{\text{dest}}^{\text{LM6000}}}{\dot{E}x_{t,\text{in}}^{\text{LM6000}}} \quad (\text{Ranging from 0 to 1}) \tag{45}$$

*Environmental effect factor* ($r_{\text{eef}}$)
Another important sustainability indicator to be reviewed is environmental effect factor which is calculated the ratio of waste exergy ratio to the exergy efficiency. Environmental impact factor indicates whether or not it damages the environment because of its unusable waste exergy output and exergy destruction.

$$\text{Environmental effect factor} = \text{Waste exergy ratio/Exergy efficiency)} \tag{46}$$

As for case A,

$$r_{\text{eef}}^{\text{case A}} = \frac{r_{\text{we}}^{\text{case A}}}{\eta_{\text{ex}}^{\text{case A}}} \tag{47}$$

And for Case B;

$$r_{\text{eef}}^{\text{case B}} = \frac{r_{\text{we}}^{\text{case B}}}{\eta_{\text{ex}}^{\text{case B}}} \tag{48}$$

*Exergetic sustainability index* ($\Theta_{\text{esi}}$)
Exergetic sustainability index is vital parameter among exergetic sustainability indicators to assess the system's sustainability level. Its function of environmental effect factor can be found out by ratio of 1 to the environmental effect factor. The range of this index is between 0 and ∞ [8,10]. The higher efficiency means low waste exergy ratio and low environmental effect factor as a result higher exergetic sustainability index. Exergy clearly helps determine efficiency improvements and reductions in thermodynamic losses attributable to a process. Measures to increase exergy efficiency can reduce environmental impact by reducing energy losses. Within the scope of exergy methods, such activities lead to increased exergy efficiency and reduced exergy losses (both waste exergy emissions and internal exergy consumptions) [8,38]. Higher efficiency in natural gas consumption allows the LM6000 GTE to contribute to exergy-based sustainability since increased efficiency reduces environmental impacts and resource requirements.

**Table 2**
Exergy values of the LM6000 GTE power plant and its component.

| Component | Inlet exergy (MW) | Outlet exergy (MW) | Fuel exergy (MW) | Product exergy (MW) | Exergy destruction (MW) | Exergy efficiency (%) | Exergy destruction ratio (%) | Fuel depletion rate (%) | Productivity lack ratio (%) | Fuel exergy factor (%) | Product exergy factor (%) | Exergetic imp. potential (MW) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | $Ex_i$ | $Ex_o$ | $F$ | $P$ | $Exd$ | $\eta$ | $X$ | $\delta$ | $\zeta$ | $f$ | $p$ | $IP$ |
| LPC | 11.62 | 10.33 | 11.62 | 10.33 | 1.29 | 88.9 | 3280 | 0.352 | 0.394 | 3168 | 3155 | 0.143 |
| HPC | 70.82 | 63.03 | 60.49 | 52.70 | 7.79 | 87.1 | 19,805 | 2124 | 2379 | 16,493 | 16,095 | 1003 |
| CC | 174.18 | 148.27 | 174.18 | 148.27 | 25.91 | 85.1 | 65,885 | 7066 | 7915 | 47,492 | 45,283 | 3856 |
| HPT | 148.27 | 146.65 | 62.71 | 61.09 | 1.62 | 97.4 | 4106 | 0.440 | 0.493 | 17,098 | 18,659 | 0.042 |
| LPT | 85.56 | 82.84 | 57.76 | 55.04 | 2.72 | 95.3 | 6925 | 0.743 | 0.832 | 15,749 | 16,808 | 0.128 |
| Case A LM6000 | 111.10 | 43.30 | 111.10 | 43.30 | 67.8 | 39 | | | | | | |
| Case B LM6000 + STC | 111.10 | 54.30 | 111.10 | 54.30 | 56.8 | 48.8 | | | | | | |

$$\text{Exergetic sustainability index} = 1/\text{Environmental effect factor} \tag{49}$$

And formulated as

$$\Theta_{esi} = \frac{1}{r_{eef}} \tag{50}$$

The sustainability indexes for two reviewed configuration can easily be obtained from Eqs. (51) and (52),

$$\Theta_{esi}^{case\ A} = \frac{1}{r_{eef}^{case\ A}} \tag{51}$$

$$\Theta_{esi}^{case\ B} = \frac{1}{r_{eef}^{case\ B}} \tag{52}$$

## 5. Results and discussion

This paper presents the exergy analysis and exergetic sustainability indicators of LM6000 GTE based power plant for base (case A) and steam turbine cycle implemented (case B) power plant configurations. To have base for the calculation of sustainability parameters, first the exergy parameters of main GTE components' such as exergy flows, exergy efficiency, product and fuel exergies, exergy destruction, exergy efficiency, exergy destruction ratio, fuel depletion rate, productivity lack, fuel exergy factor, product exergy factor and potential improvement rates are calculated by using Eqs. (16)–(32) based on GTE actual data [33].

The obtained exergy parameters are presented in Tables 1 and 2 and Figs. 3–6. As can be seen in Fig. 3, the exergy efficiencies of LPC, HPC, combustor, LPT, and HPT are calculated as 89%, 87.1%, 85.1%, 97.4% and 95.3% respectively. Owing to their high isentropic

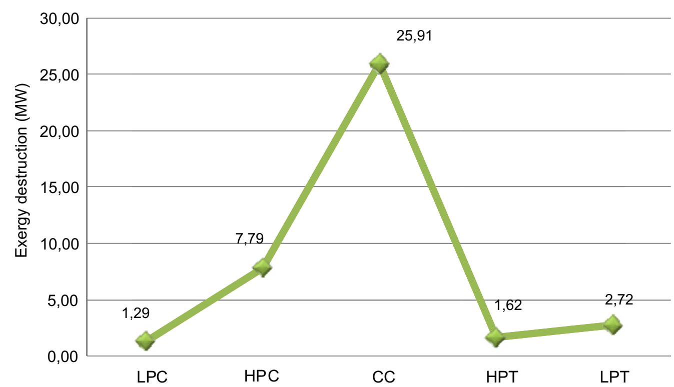


**Fig. 4.** Exergy destruction rates of LM6000 GTE main engine components.

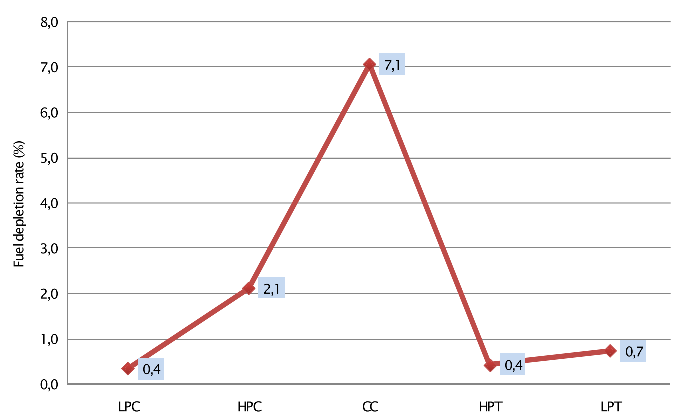


**Fig. 5.** Fuel depletion ratios of LM6000 GTE main each engine component.

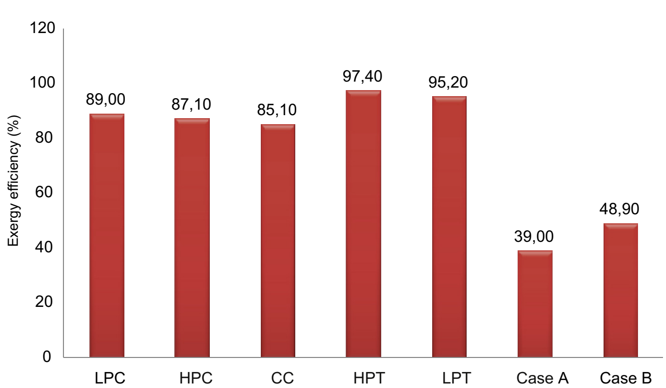


**Fig. 3.** Exergy efficiencies of LM6000 GTE main engine components.

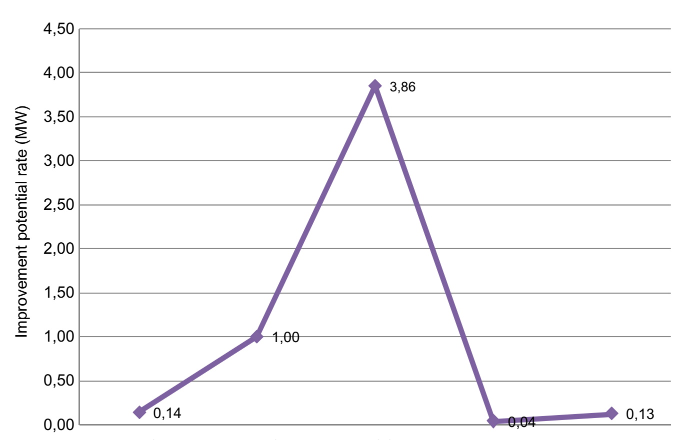


**Fig. 6.** LM6000 GTE main engine components improvement potentials.

efficiencies (between 80% and 95%), LPC, HPC, LPT and, HPT have higher exergy efficiencies Meanwhile the exergy efficiency of whole system is found to be as 39% for GTE based power plant (case A) and as 49% for GTE based power plant with steam turbine cycle implemented (case B). Although 43.3 MW electricity power is generated from base power plant, 54.3 MW power can be generated after steam turbine cycle implementation. Thus, the exergy efficiency of the complete power plant improves about 10% with the aid of steam turbine cycle in which the hot exhaust gases are processed that 11 MW of additional electricity power is procured by steam turbine generator.

Exergy destructions of GTE components are presented in Fig. 4, as noted greatest exergy destruction occurs in combustor by 25.91 MW which is due to the internal irreversibility's although it has relatively higher exergy efficiency with 85.1%. The exergy destruction rates are counted about 7.79 MW for HPC, 1.29 MW for LPC, 1.62 MW for HPT and 2.72 MW for LPT that the total exergy destruction reaches to 39.33 MW for LM6000 GTE power plant. The most irreversible components are combustor and HPC, with exergy destruction rates of 65.88% and 19.8%, respectively.

Another exergy parameter, fuel depletion ratios for the engine components are presented in Fig. 5. HPT and LPC has minimum fuel depletion ratio with 0.4% whereas combustor has 7.1%. Fig. 6 presents the improvement potentials of GTE main components. As noted combustor has highest exergetic improvement potential with 3.86 MW whereas lowest value is obtained in HPT by 0.04 MW.

Exergetic sustainability indicators for case A and case B power plants are derived from exergy parameters by using Eqs. (32)–(52). The results are presented in Table 3 and Fig. 9.

In this regard, exergetic sustainability indicators such as exergy efficiency, waste exergy ratio, recoverable exergy rate, exergy destruction factor, environmental effect factor and exergetic sustainability index are obtained for the reviewed two GTE power plant configurations.

**Table 3**
Exergetic sustainability parameters for case A and case B LM6000 GTE based power plants.

| | Case A | Case B |
|---|---|---|
| Total inlet exergy (MW) | 111.3 | 111.3 |
| Useful exergy (MW) | 43.3 | 54.3 |
| Loss exergy (MW) | 27.2 | 16.2 |
| Total destructed exergy (MW) | 39.33 | 39.33 |
| Total waste exergy (MW) | 66.53 | 55.53 |
| Exergy efficiency | 0.389 | 0.488 |
| Waste exergy ratio | 0.598 | 0.499 |
| Recoverable exergy rate | 0.220 | 0.131 |
| Exergy destruction factor | 0.353 | 0.353 |
| Environmental effect factor | 1.536 | 1.023 |
| Exergetic sustainability index | 0.651 | 0.978 |

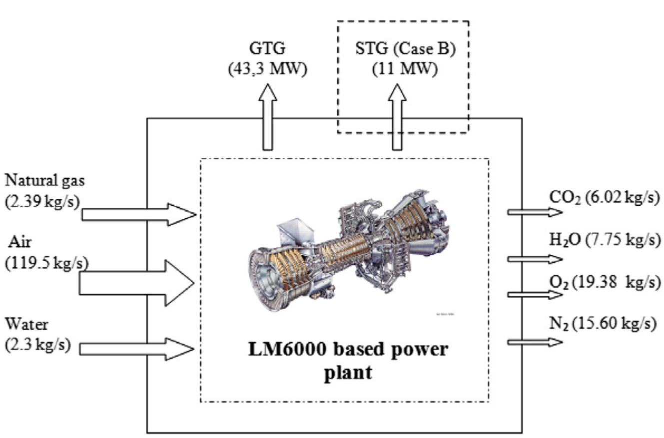


**Fig. 7.** LM6000 GTE based power plant (Case A and Case B) mass and energy flows.

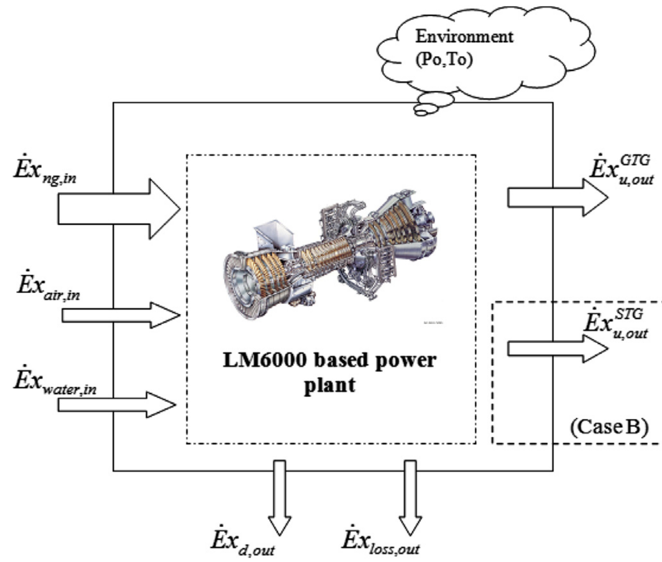


**Fig. 8.** LM6000 GTE based power plant exergy balance (Case A and Case B).

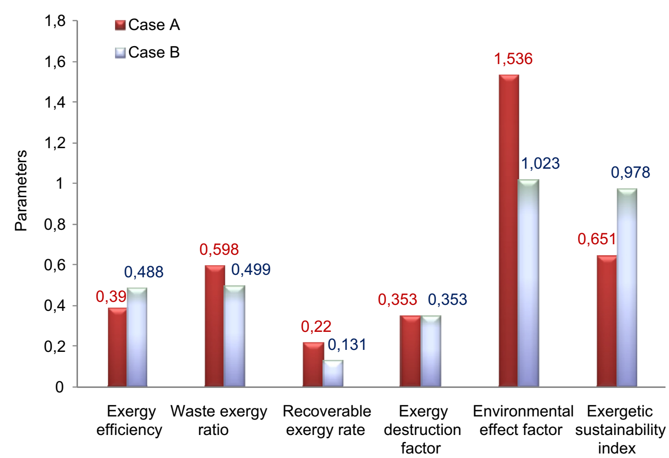


**Fig. 9.** Exergetic sustainability indicators of case A and case B LM6000 GTE based power plants.

As noted the steam turbine cycle involvement improves the exergy efficiency from 39% to 48.8% as of increase in the generated electricity power value that evidently improves the other exergetic sustainability indicators significantly.

The waste exergy rate is obtained as 66.5 MW along with 59.8% waste exergy ratio for case A, although they're as 55.53 MW and 49.9% for case B. One notice that waste exergy ratio decreases by 10% which's almost the same amount with efficiency increase. Some part of waste or loss exergy can be recoverable for heating purposes provided that additional investments and systems are applied.

Recoverable exergy rates are assessed around 24.5 MW and 14.6 MW for case A and case B LM6000 GTE based power plant configurations with an assumption of system efficiency as 90%. The recoverable exergy ratio of case B is less than case A, since the power plant with steam turbine cycle has higher efficiency and lower waste exergy rate.

Exergy destruction factor is calculated as 36.6% for GTE power plant. Environmental effect factor for case A and case B are found to be as 1.536 and 1.023, respectively.

As last reviewed exergetic sustainability parameter, exergetic sustainability index is obtained as 0.651 for case A and 0.978 for case B LM6000 GTE based power plants.

## 6. Conclusions

Exergy and exergetic sustainability analysis of GTE based power plant provides valuable information to identify the level of sustainability and environmental impact. In this study, exergy and exergetic sustainability analyses of two power plant configuration, case A for LM6000 GTE based power plant, case B for LM6000 GTE based power plant with steam turbine cycle have been performed. For this purpose, the developed exergetic sustainability indicators are exergetic efficiency, waste exergy ratio, exergy destruction ratio, environmental effect factor and exergetic sustainability index.

The main conclusions that can be drawn from this study is outlined as below,

a) The steam turbine cycle implementation into classic GTE based power plant leads to higher overall efficiency thus better exergetic sustainability index is obtained. As a result of additional 11 MW electricity power generation by steam turbine cycle the exergy efficiency reaches to 48.8% although it is 39% for base power plant configuration.
b) The increase of useful product or electricity power for the same fuel consumption decreases the waste exergy rate from power plant that results in improvement in exergetic sustainability parameters. Waste exergy ratio is reduced by 10% with steam cycle.
c) Recoverable exergy ratios are obtained about 22% and 13.1% for case A and case B power plants respectively. GTE based power plant's exergetic sustainability indicators can even be further improved provided that discharged exhaust gases exergy are used for heating or other purposes that will minimize the waste exergy rate leading to higher overall exergy efficiency.
d) Environmental effect factor improves by around 50% in case B power plant with steam cycle. Finally, exergetic sustainability index is computed as 0.651 for case A and 0.978 for case B power plant configurations.
e) Any increase in efficiency improves the exergetic sustainability. However, any increase in waste exergy ratio and exergy destruction factor results in increasing of environmental effect factor and hence, decreases the sustainability. These parameters are expected to quantify how GTE based power plant become more environmentally benign and sustainable.

Second law analysis plays an important role in any evaluation of the sustainability of GTE based power plant. The exergy-based environmental analysis can help to improve the environmental performance of GTE based power plant, and consequently should be considered in future assessments. Other indicators or indices can be used to access to characteristics of the GTE based power plants, namely the Resource Indicator, the Environmental Indicator, the Social Indicators, Economic Indicator. Finally, a number of additional indicators can also be derived for GTE based power plants for further study.

## Acknowledgments

The authors acknowledge the support provided by Anadolu University and Turkish Engine Industries (TEI).

## Nomenclature

| | |
|---|---|
| $c_p$ | specific heat (kJ kg$^{-1}$ K$^{-1}$) |
| GTE | gas turbine engine |
| STG | steam turbine generator |
| GTG | gas turbine generator |
| STC | steam turbine cycle |
| $\dot{E}$ | energy rate (MW) |
| $\dot{E}x$ | exergy rate (MW) |
| $f$ | exergy destruction factor |
| $h$ | specific enthalpy (kJ kg$^{-1}$) |
| $I\dot{P}$ | exergetic improvement potential rate (MW) |
| LHV | lower heating value of fuel (kJ kg$^{-1}$) |
| $\dot{m}$ | mass flow rate (kg s$^{-1}$) |
| $P$ | pressure (kPa) |
| $R$ | specific gas constant (kJ kg$^{-1}$ K$^{-1}$) |
| $r$ | waste exergy ratio, recoverable exergy rate, environmental effect factor |
| $s$ | specific entropy (kJ kg$^{-1}$ K$^{-1}$) |
| SFC | specific fuel consumption (g kN$^{-1}$ s$^{-1}$) |
| $T$ | temperature (K) |
| $V$ | velocity of stream (m s$^{-1}$) |
| $\dot{W}$ | work rate (MW) |
| $\delta$ | fuel depletion ratio |
| $\Theta$ | exergetic sustainability index |
| $\chi$ | relative irreversibility |
| $\eta$ | efficiency |

*Indices*

| | |
|---|---|
| $a$ | air |
| $B$ | bleed air |
| $c$ | compressor |
| $cc$ | combustion chamber |
| $ch$ | chemical |
| cfm | CFM turbofan engine |
| $d$ | destroyed, destruction |
| eef | environmental effect factor |
| esi | exergetic sustainability index |
| ex | exergy |
| exd | exergy destruction |
| $f$ | fuel |
| LPC | low pressure compressor |
| HPC | high pressure compressor |
| LPT | low pressure turbine |
| HPT | high pressure turbine |
| EN | exhaust nozzle |
| $i$ | successive number of elements |
| in | inlet |
| kn | kinetic |
| out | outlet |
| ph | physical |
| pt | potential, constant pressure |
| LD | loss and destruction |
| re | recoverable |
| $t$ | total |
| we | waste |
| $u$ | useful |

## References

[1] Dincer I, Rosen MA. Thermodynamic aspects of renewable and sustainable development. Renewable and Sustainable Energy Reviews 2005;9(2):169–89.
[2] Rosen MA. Energy sustainability: a pragmatic approach and illustrations. Sustainability 2009;1:55–80. http://dx.doi.org/10.3390/su1010055.
[3] Turgut ET, Karakoc TH, Hepbasli A, Rosen MA. Exergy analysis of a turbofan aircraft engine. International Journal of Exergy 2009;6(2):181–99.
[4] Mert MS, Dilmac OF, Ozkan S, Karaca F, Bolat E. Exergoeconomic analysis of a cogeneration plant in an iron and steel factory. Energy 2012;46:78–84.
[5] Rosen MA, Dincer I. Exergoeconomic analysis of power plants operating on various fuels. Applied Thermal Engineering 2003;23:643–58.

[6] Balli O, Aras H. Energetic and exergetic performance evaluation of a combined heat and power system with the micro gas turbine (MGTCHP). International Journal of Energy Research 2007;31(14):1425–40.
[7] Genoud S, Lesourd JB. Characterization of sustainable development indicators for various power generation technologies. International Journal of Green Energy 2009;6(3):257–67.
[8] Midilli A, Dincer I. Development of some exergetic parameters for PEM fuel cells for measuring environmental impact and sustainability. International Journal of Hydrogen Energy 2009;34:3858–72.
[9] Aydin H. Technical evaluation report-i, natural and applied science [Doctorate thesis]. Eskisehir, Turkey: Anadolu University; 2012.
[10] Midilli A, Kucuk H, Dincer I. Environmental and sustainability aspects of a recirculating aquaculture system. Published online in Wiley Online Library, wileyonlinelibrary.com; 2011.
[11] Midilli A, Dincer I, Ay M. Green energy strategies for sustainable development. International Journal of Energy Policy 2006;34:3623–33.
[12] Midilli A, Dincer I. Hydrogen as a renewable and sustainable solution in reducing global fossil fuel consumption. International Journal of Hydrogen Energy 2008;33:4209–22.
[13] Ahmadi P, Dincer İ, Rosen M,A. Exergy, exergoeconomic and environmental analyses and evolutionary algorithm based multi-objective optimization of combined cycle power plants. Energy 2011;36:5886–98.
[14] Ahmadi P, Dincer I. Exergoenvironmental analysis and optimization of a cogeneration plant system using Multimodal Genetic Algorithm (MGA). International Journal of Energy 2010;35:5161–72.
[15] Hamed OA, Al-Washmi HA, Al-Otaibi HA. Thermoeconomic analysis of a power-water cogeneration plant. International Journal of Energy 2006;31:2699–709.
[16] Bracco S, Siri S. Exergetic optimization of single level combined gas steam power plants considering different objective functions. International Journal of Energy 2010;35:5365–73.
[17] Balli O, Aras H, Hepbasli A. Exergetic and exergoeconomic analysis of an Aircraft Jet Engine (AJE). International Journal of Exergy 2008;5(56):567–81.
[18] Aydin H, Turan O, Midilli A, Karakoc TH. Exergetic and exergo-economic analysis of a turboprop engine: a case study for CT7–9C. International Journal of Exergy 2012a;11(1):69–88.
[19] Aydin H, Turan O, Karakoc TH, Midilli A. Component-based exergetic measures of an experimental turboprop/turboshaft engine for propeller aircrafts and helicopters. International Journal of Exergy 2012b;11(3):322–48.
[20] Bilgen E. Exergetic and engineering analyses of gas turbine based cogeneration systems. International Journal of Energy 2000;25:1215–29.
[21] Khaliq A, Dincer I. Energetic and exergetic performance analyses of a combined heat and power plant with absorption inlet cooling and evaporative after cooling. Energy 2011;36:2662–70.
[22] Abusoglu A, Kanoglu M. Exergetic and thermoeconomic analyses of diesel engine powered cogeneration: part 1 – Formulations. Applied Thermal Engineering 2009;29:234–41.
[23] Turan O. Effect of reference altitudes for a turbofan engine with the aid of specific-exergy based method. International Journal of Exergy 2012a;11(2):252–70.
[24] Turan O. Exergetic effects of some design parameters on the small turbojet engine for unmanned air vehicle applications. Energy, The International Journal 2012b;46:51–61.
[25] Morosuk T, Tsatsaronis G. Comparative evaluation of LNG – based cogeneration systems using advanced exergetic analysis. Energy 2011;36:3771–8.
[26] Deng S, Jin H, Cai R, Lin R. Novel cogeneration power system with liquefied natural gas (LNG) cryogenic exergy utilization. Energy 2004;29:497–512.
[27] Amer M, Behbahaninia A, Tanha AA. Thermodynamic analysis of a trigeneration system based on micro-gas turbine with a steam ejector refrigeration system. Energy 2010;35:2203–9.
[28] Aljundi IH. Energy and exergy analysis of a steam power plant in Jordan. Applied Thermal Engineering 2009;29:324–8.
[29] LM6000 on-site operation and maintenance manual, GEK 105059, vol. 1; 2003.
[30] General electric LM6000. http://en.wikipedia.org/wiki/; 5 Dec 2012.
[31] Cengel YA, Boles MA. Termodinamik: Muhendislik Yaklasımıyla. Turkey: Literature Press; 2008 [in Turkish].
[32] Moran MJ, Shapiro HN. Fundamentals of engineering thermodynamics. New York: Wiley; 1995.
[33] LM6000 Quick reference guide.
[34] Bejan A, Tsatsaronis G, Moran MJ. Thermal design and optimization. New York, USA: Wiley; 1996.
[35] Kotas TJ. The exergy method of thermal plant analysis. Reprint ed. Malabar, Florida: Krieger; 1995.
[36] Moran MJ. Availability analysis: a guide to efficient energy use. NJ (USA): Prentice- Hall; 1982.
[37] Van Gool W. Energy policy: fairly tales and factualities. In: Soares ODD, Martins da Cruz A, Costa Pereira G, Soares IMRT, Reis AJPS, editors. Innovation and technology-strategies and policies. Dordrecht: Kluwer; 1997. p. 93–105.
[38] Rosen MA, Dincer I, Kanoglu M. Role of exergy in increasing efficiency and sustainability and reducing environmental impact. Energy Policy 2008;36(1):128–37.